REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*

2. REPORT TYPE
Technical Papers

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
3058

5e. TASK NUMBER
RF9A

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

8. PERFORMING ORGANIZATION REPORT

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

20030123 037

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Leilani Richardson
Unclassified	Unclassified	Unclassified	A		19b. TELEPHONE NUMBER *(include area code)* (661) 275-5015

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

21 separate items enclosed

FIED | FILE

3058 RFC A

MEMORANDUM FOR PR (In-House Publication)

FROM: PROI (TI) (STINFO) 30 November 1999

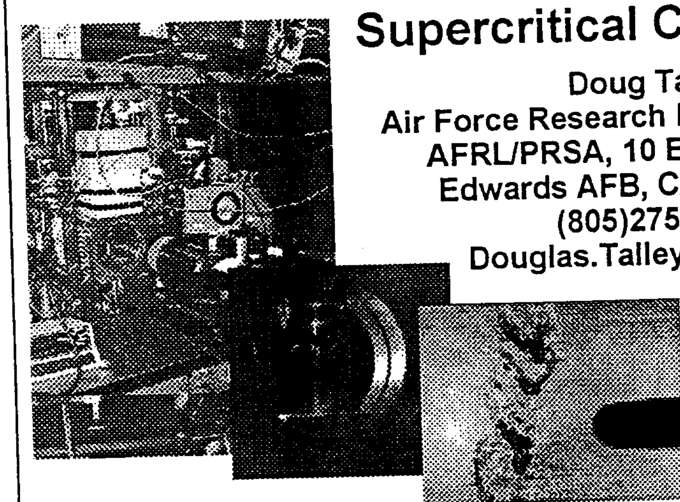
SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-1999-0226**
Talley, D., "Basic Research in Supercritical Combustion" (BFI)

49th JANNAF Propulsion Meeting (Tucson, AZ, 14-16 Dec 1999) **(Statement A)**

BRIEFING FOR INDUSTRY
16 Dec 1999

Basic Research in Supercritical Combustion

Doug Talley
Air Force Research Laboratory|AFRL
AFRL/PRSA, 10 E. Saturn Blvd.
Edwards AFB, CA 93524-7660
(805)275-6174
Douglas.Talley@ple.af.mil



6.1 Objectives

- Determine the mechanisms which control the breakup, transport, mixing, and combustion of sub- and super-critical droplets, jets, and sprays.

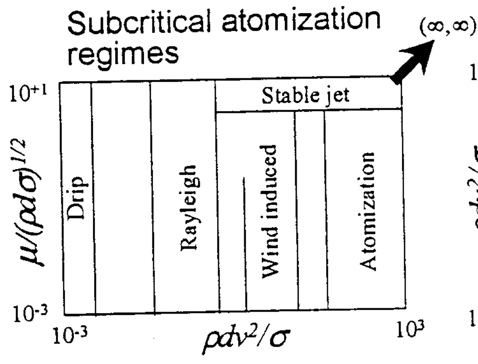
	Prior	FY99	FY00	FY01
6.1 Funding ($1,000's)	1318	150	141	141

The Problem

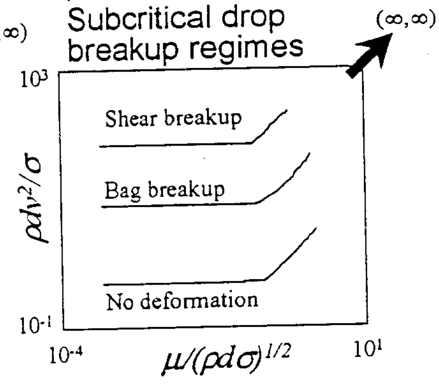
- It is often advantageous to operate combustion chambers at pressures exceeding the critical pressure of one or both propellants.
  - Higher chamber pressures lead to greater performance (Isp).
- At supercritical pressures, the distinct difference between gas and liquid phases disappears.
  - Conventional "spray combustion" experience no longer applies.
- It is not known how to replace conventional "spray combustion" models in engine design codes.
  - *The lack of understanding leads to potentially large engine design errors.*

The Problem (con't)

Subcritical atomization regimes



Subcritical drop breakup regimes



Surface tension σ vanishes at supercritical conditions. Conventional atomization and breakup parameters become *infinite*, where no data exists.

Supercritical atomization and breakup regimes are *unknown.*

The Problem (con't)

- Supercritical combustion is complicated by several factors not present in subcritical combustion:
  - Vanishing surface tension.
  - Equivalent gas and liquid phase densities.
  - Strongly enhanced gas / liquid solubility.
  - Different reaction kinetics.
  - Mixing induced critical point variations.
  - Property computation / singular behavior.
    - Zero enthalpy of vaporization.
    - Infinite specific heat (Cp).
    - Infinite compressibility.
- *Deeply fundamental questions such as whether droplets can even exist were hotly debated when this work began.*

Technical Approach

- Windowed pressure vessel operating at supercritical pressures.
- Cryogenic fluid capability (LOX, LN2)
- Capability to produce supercritical droplets and jets.
- Shadowgraph, Schlieren, and Raman visualization of concentration fields.
- Capability to drive flows with an acoustic driver

Air Force Research Laboratory|AFRL

Payoffs

Provide alternatives to trial and error development

- *Performance:* Injector related design uncertainties translate to 3-6 sec Isp on a booster class LOX/H2 engine.
  - Comparison: IHPRPT 2010 Isp objective is 13.5 sec.
  - 3-6 sec Isp buys 1.6 - 3.3 *tons* payload on the Space Shuttle Main Engine (SSME) worth \$20-40M *per launch.*
- *Operability and Lifetime:* Injector related performance deficit required SSME turbopumps to be run at 105% rated power, increasing pump stress.
  - Pumps are the most expensive SSME maintenance item.
  - Turb. blade cracking problem is also probably inj. related.
- *Instability:* Injector related Saturn F-1 instability problem required over 800 full scale tests to solve.
  - Present day costs: over \$750K per test. Total: \$600 million.

Trial-and-error approaches risk significant cost overruns that can no longer be afforded

OK ← Public release info?

Air Force Research Laboratory|AFRL

FY99 Accomplishments

For subcritical and supercritical mixing layers:

- Measured the growth rate for a wide variety of propellant combinations
- Developed comprehensive model to predict mixing layer growth rates over four orders of magnitude in density ratio
- Performed fractal analysis of mixing layer geometry
- Installed and performed initial Raman measurements of species distributions.

Evolution of Mixing Layers in Transition from a Subcritical to a Supercritical State

Acknowledgements:

Bruce Chehroudi

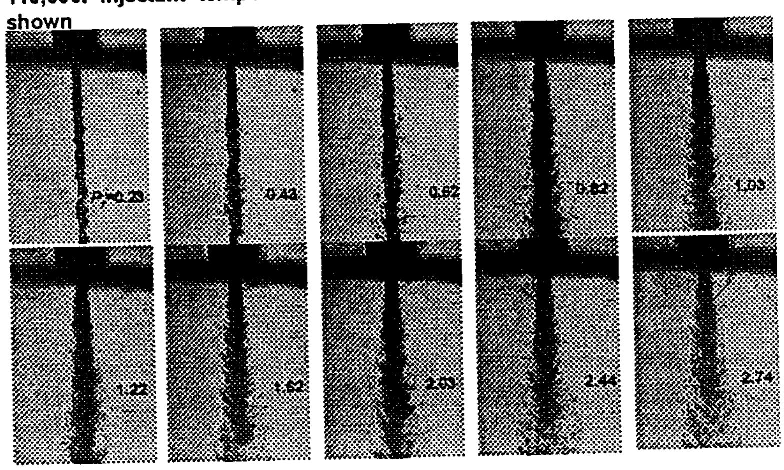
Rich Cohn

Roger Woodward

Ed Coy

N_2 into N_2

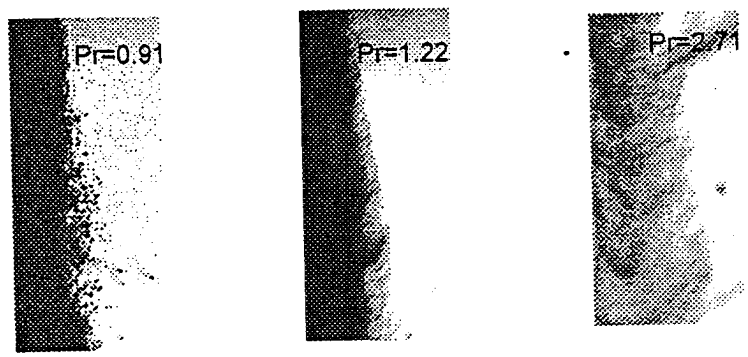
Back-illuminated images. Chamber is at a fixed supercritical temperature of 300 K but varying sub- to supercritical pressures ($P_{critical}$ = 3.39 MPa). Re = 25,000 to 75,000. Injection velocity: 10-15 m/s. Froude number = 40,000 to 110,000. Injectant temperature = 99 to 120 K. Reduced pressures are shown



PRESSURE DEPENDENT MIXING LAYER STRUCTURE

Nitrogen/nitrogen system (P_{cr} = 3.39 MPa, T_{cr} = 126 K)

T_{inj} = 128 K, T_{amb} = 300 K, mass flow = 350 mg/s

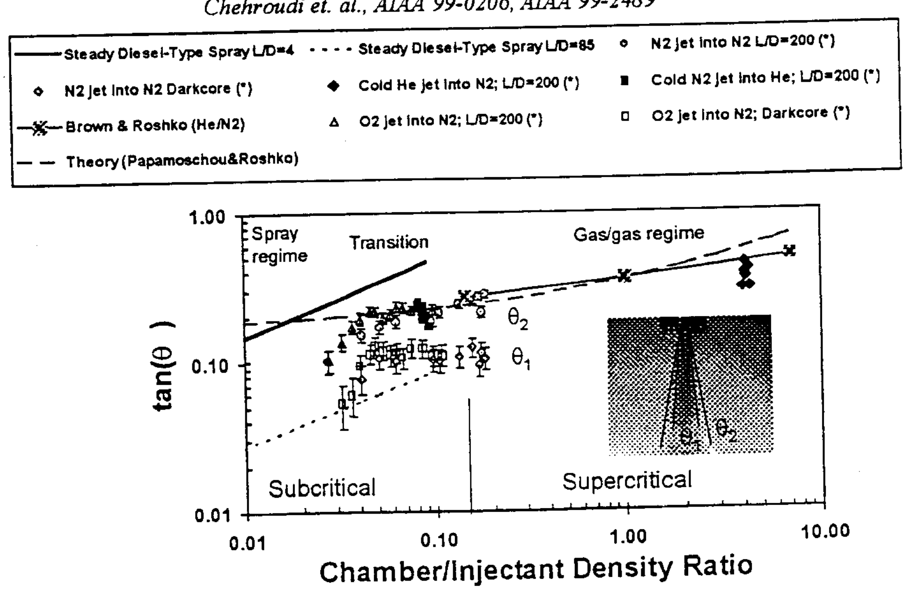


Low Pres.	***Mod. Pres.***	***High Pres.***
Subcritical	***Supercritical***	***Supercritical***
Droplets	Ligaments	Gas layers

Air Force Research Laboratory

Sub- and Super-critical Mixing Layer Physics

Chehroudi et. al., AIAA 99-0206, AIAA 99-2489



Characteristic Times

- Characteristic bulge formation time (τ_b) at the jet interface (Tseng et al.): $(\rho_l L^3/\sigma)^{1/2}$; ρ_l , L, σ are liquid density, characteristic dimension of turbulent eddy, and surface tension, respectively.
- Characteristic time for gasification (τ_g) (D-square law): D^2/K; D and K are drop diameter and vaporization constant.
- A Hypothesis: If these two characteristic times (calculated for appropriate length scales) are comparable then an interface bulge may not be separated as an unattached entity (onset of the gas-jet behavior at supercritical condition)

Air Force Research Laboratory|AFRL

Similar equation format for different cases

- Theoretical isothermal liquid spray growth rate (θ_s) based on Orr-Sommerfeld equation and stability analysis to find the wavelength of the most unstable interface wave:
  $\theta_s \cong 0.27\,[0 + (\rho_g/\rho_l)^{0.5}]$
- Papamoschou/Rashko theory for incompressible variable-density gaseous mixing layer/jet:
  $\theta_{P/R} \cong 0.17\,[1 + (\rho_g/\rho_l)^{0.5}]$
- Dimotakis theory for incompressible variable-density gaseous mixing layer/jet:
  $\theta_D \cong 0.212\,[0.59 + (\rho_g/\rho_l)^{0.5}]$
- ALL HAVE THE SQUARE ROOT OF DENSITY RATIO AND THE SAME EQUATION FORMAT

Correlation

- Based of the information of the previous slide the following "intuitive/smart" equation is proposed for both sub- and supercritical measured growth rates:

$\theta_{Ch} \cong 0.27\ [\ (\tau_b/(\tau_b+\tau_g)) + (\rho_g/\rho_l)^{0.5}]$

Note:

- For isothermal liquid case: $\tau_g >> \tau_b$ and $\tau_g \rightarrow \infty$. It then collapses to the isothermal spray case.
- For subcritical the $(\tau_b/(\tau_b+\tau_g))$ is calculated until it reaches 0.5. After that it is maintained constant at 0.5 for supercritical gas-like jet. The transition point is found to be approximately when $(\tau_b/(\tau_b+\tau_g)) \cong 0.5$ (i.e. $\tau_b \cong \tau_g$).

Correlation (con't)

- $(\tau_b/(\tau_b+\tau_g))$ is assumed to be a dominant function of the density ratio (ρ_g/ρ_l); i.e. $\tau_b/(\tau_b+\tau_g)) = F(\rho_g/\rho_l)$.

- The function F is only calculated for the N2-into-N2 case and is taken to be the same for other (N_2-into-He ans N_2-into-Ar) cases. That is, for example, for N_2-into-He :

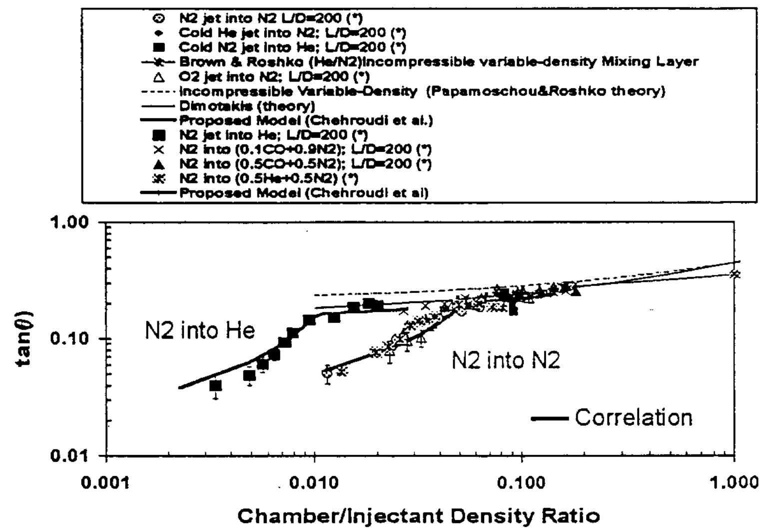
$\theta_{Ch} \cong \mathbf{0.27}\ [\ G(\rho_g/\rho_l) + (\rho_g/\rho_l)^{0.5}]$ where $G(\rho_R) = F(\rho_R')$

$\rho_R = (\rho_g/\rho_l)$; $\rho_R' = \rho_R - (1-X)\rho_R = X\rho_R$

X=1.0 for N_2-into-N_2; **X=0.2** for N_2-into-He ; **X=1.2** for N_2-into-Ar.

Air Force Research Laboratory|AFRL

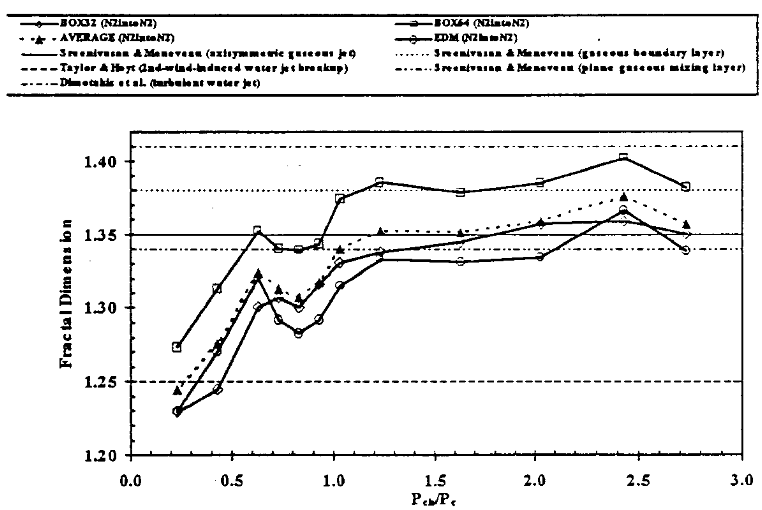
Empirical Correlation Results



Air Force Research Laboratory|AFRL

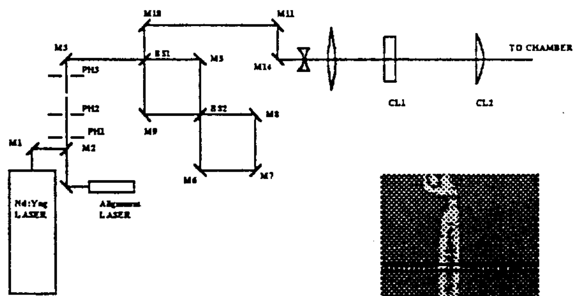
Fractal Dimension vs Reduced Pressure

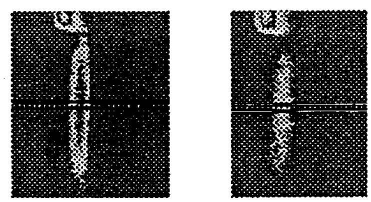
Chehroudi et. al., AIAA 99-2489



— Air Force Research Laboratory|AFRL —

Raman Imaging Set-up



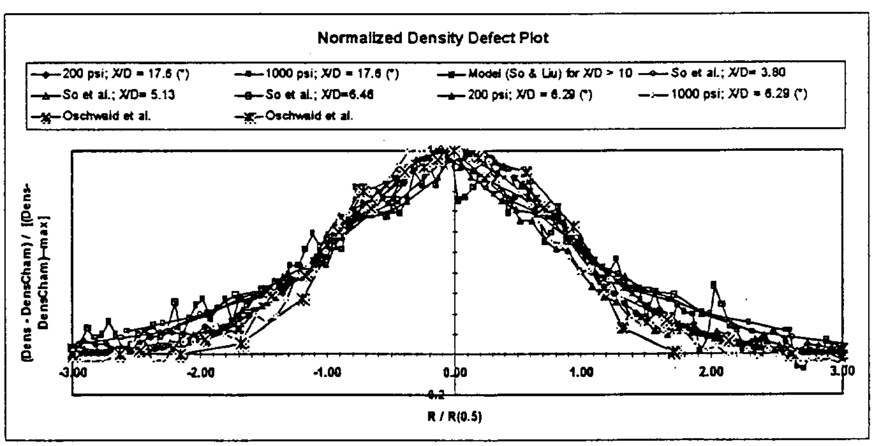


Subcritical N_2 Jet   Supercritical N_2 Jet

— Air Force Research Laboratory|AFRL —

Preliminary Raman Results

- Plot contains a theoretical model, supercritical jets from AFRL and DLR, and gas jets
- Self-similarity behavior is observed



Planned for FY00

- Complete Raman species measurements; reduce and analyze data.
- Install acoustic drivers and investigate the effect of acoustic waves.

Summary and Conclusions

- Structural differences in cryogenic jets have been observed below and above the thermodynamic critical point.
- Liquid-Jet like appearance occurs up to near the critical point, similar to second wind-induced liquid jet breakup regime.
- Gas-jet like appearance occurs above the critical point. No drops are observed.
  - Supercritical spreading rate measurements agree quantitatively with incompressible variable density mixing layer experiments and theory.
  - Supercritical fractal dimensions agree quantitatively with gas jet measurements.
- New and existing mixing layer growth rate experiments and theory have for the first time been consolidated into a single plot as a function of density ratio, where the density ratio spans three orders of magnitude.
- A physical mechanism and correlation have been proposed to describe the transition from spray to gas jet behavior.

Summary and Conclusions (con't)

- Preliminary analysis of Raman data indicates self-similar spreading behavior much like a gas jet.